Search for Partonic EoS in High-Energy Collisions

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Many Thanks to Organizers!

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Outline

//Talk/2005/01Hirschegg05//

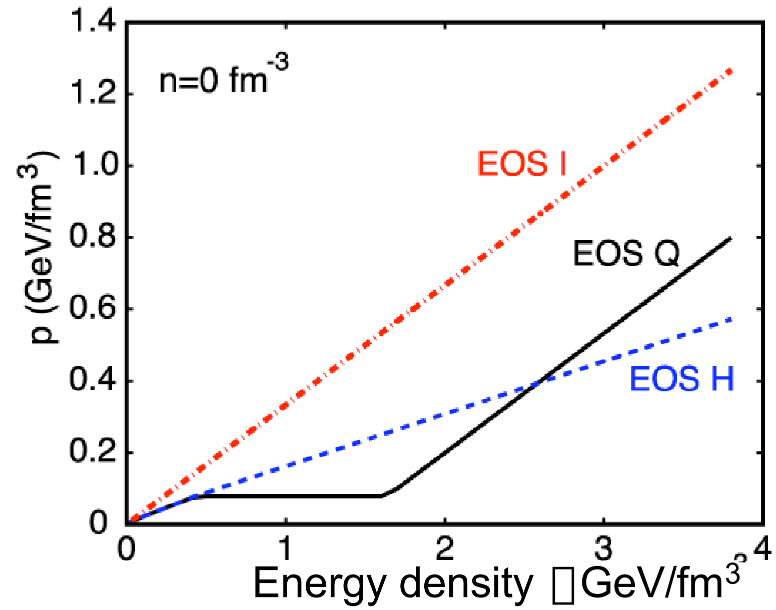
- Motivation
- Bulk properties - ∂P_{QCD}
  - Hadron spectra and elliptic flow
  - NCQ scaling: deconfinement
  - Heavy flavor collectivity: thermalization
- Summary & Outlook

Equation of State

$$\partial_\mu T^{\mu\nu} = 0$$

$$\partial_\mu j^\mu = 0 \qquad j^\mu(x) = n(x)u^\mu(x)$$

$$T^{\mu\nu} = [\varepsilon(x) + p(x)]u^\mu u^\nu - g^{\mu\nu}p(x)$$



With given degrees of freedom, the EOS - the system response to the changes of the thermal condition - is fixed by its ***p*** and ***T*** **(*ε*)**.

Equation of state:

- **EOS I** : relativistic ideal gas: $p = \varepsilon/3$
- **EOS H**: resonance gas: $p \sim \varepsilon/6$
- **EOS Q**: Maxwell construction:
  T_{crit}= 165 MeV, $B^{1/4}$ = 0.23 GeV
  ε_{lat}=1.15 GeV/fm^3

P. Kolb et al., Phys. Rev. ***C62****, 054909 (2000).*

Pressure, Flow, …

$$\tau d\sigma = dU + pdV$$

σ – entropy; p – pressure; U – energy; V – volume

$\tau = k_B T$, thermal energy per dof

In high-energy nuclear collisions, *interaction* among *constituents* and *density distribution* will lead to:

pressure gradient $\Rightarrow$ collective flow

- number of degrees of freedom (dof)
- Equation of State (EOS)
- No thermalization is needed – pressure gradient only depends on the ***density gradient and interactions***.
- Space-time-momentum correlations!

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Collectivity, Local thermalization

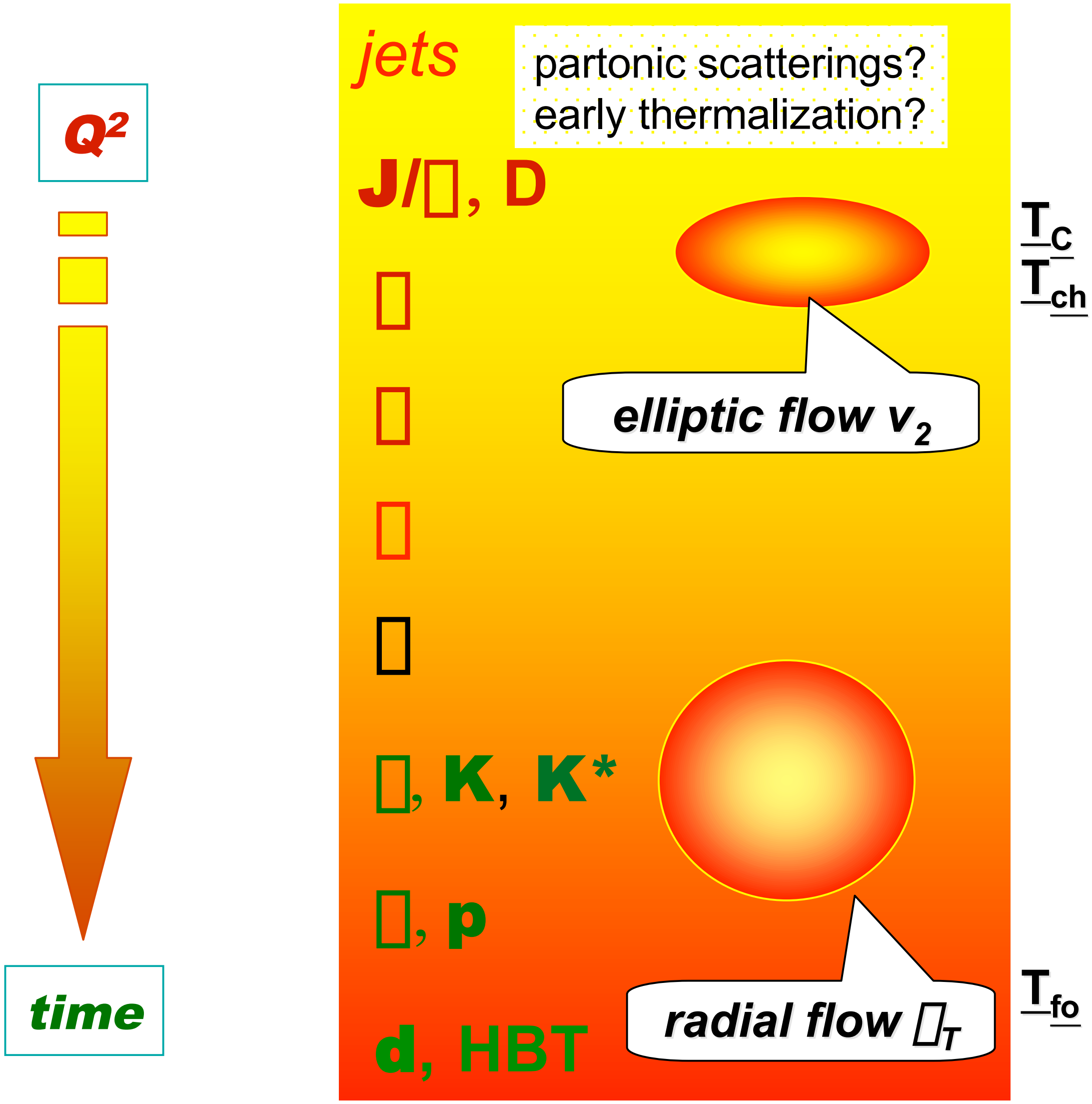
Hydrodynamic Flow	=	Collectivity	Local Thermalization

High-energy Nuclear Collisions

Initial Condition
- initial scatterings
- baryon transfer
- E_T production
- parton dof

System Evolves
- parton interaction
- parton/hadron expansion

Bulk Freeze-out
- hadron dof
- interactions stop



High-energy Nuclear Collisions

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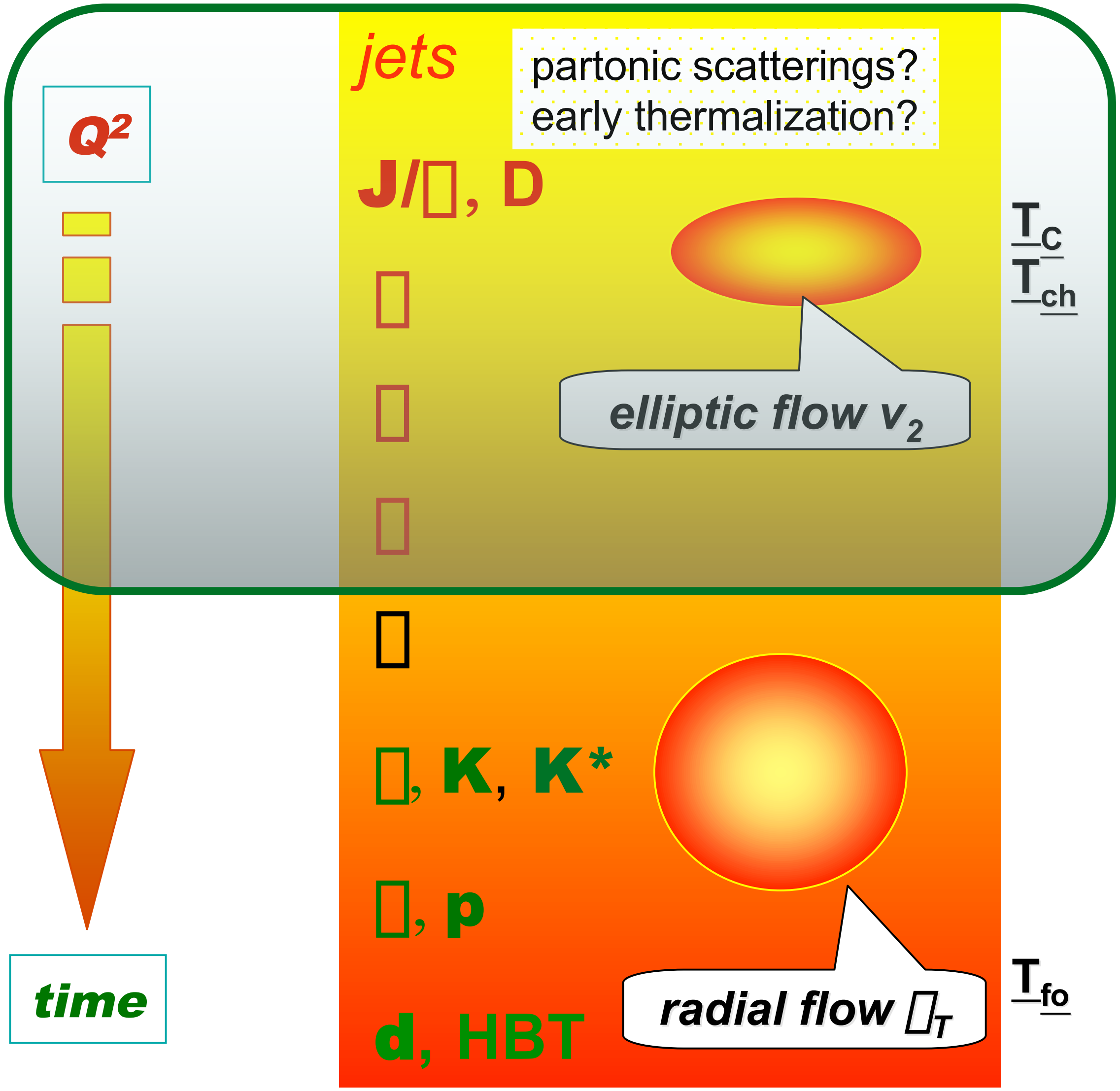


Transverse Flow Observables

$$\frac{dN}{p_t dp_t dy d\phi} = \frac{1}{2\pi}\frac{dN}{p_t dp_t dy}\left[1 + \sum_{i=1} 2v_i \cos(i\phi)\right]$$

$$p_t = \sqrt{p_x^2 + p_y^2}, \qquad m_t = \sqrt{p_t^2 + m^2}$$

As a function of particle mass:

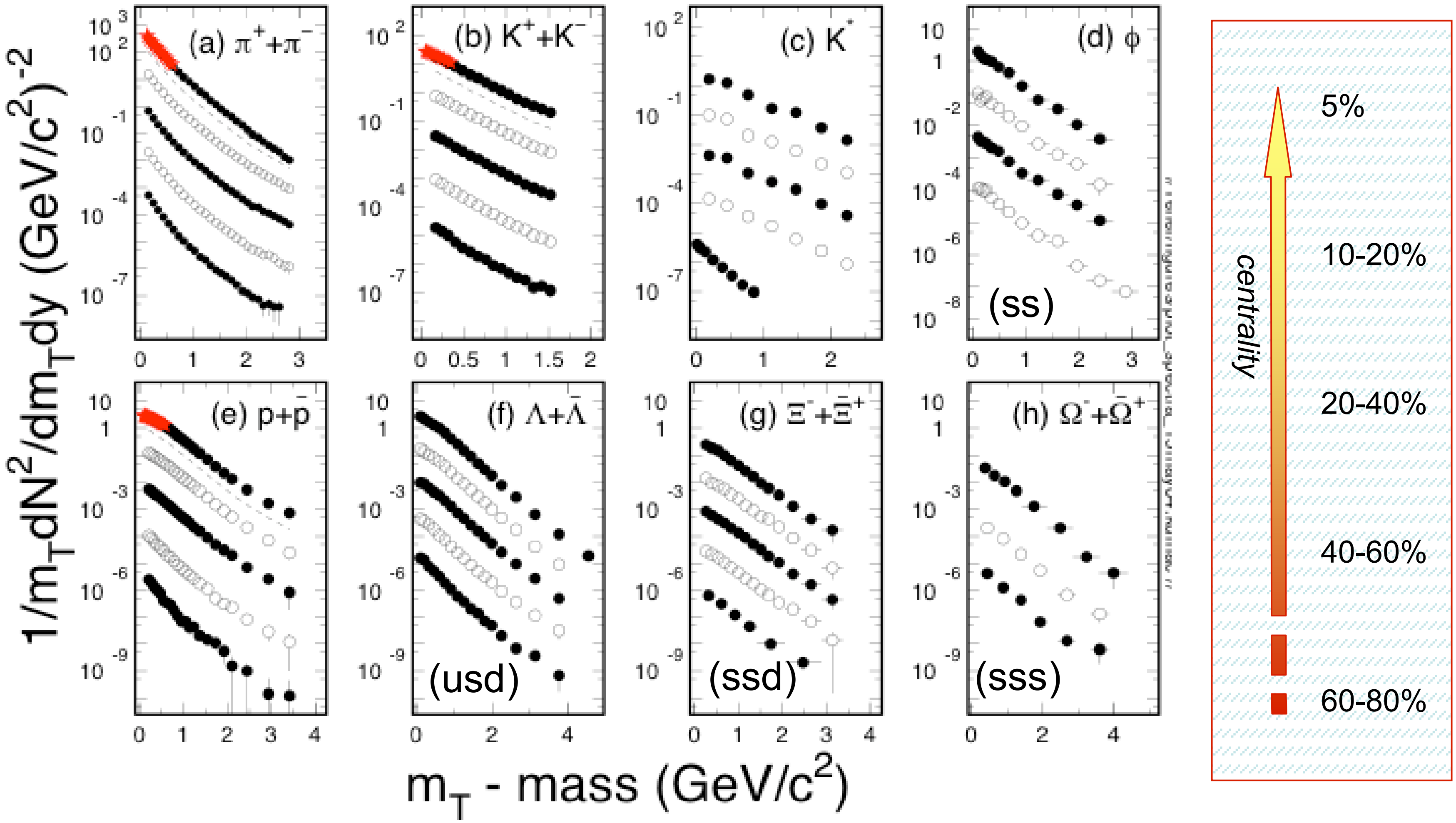
- Directed flow (v_1) – early *see Markus Oldenburg's talk*
- Elliptic flow (v_2) – early
- Radial flow – integrated over whole evolution

Note on collectivity:

1) Effect of collectivity is accumulative – final effect is the sum of all processes.
2) Thermalization is not needed to develop collectivity - pressure gradient depends on ***density gradient*** and ***interactions***.

Hadron Spectra from RHIC

mid-rapidity, p+p and Au+Au collisions at 200 GeV



$$m_T = \sqrt{p_T^2 + m^2}$$

Results from BRAHMS, PHENIX, and STAR experiments

Thermal model fit

Source is assumed to be:

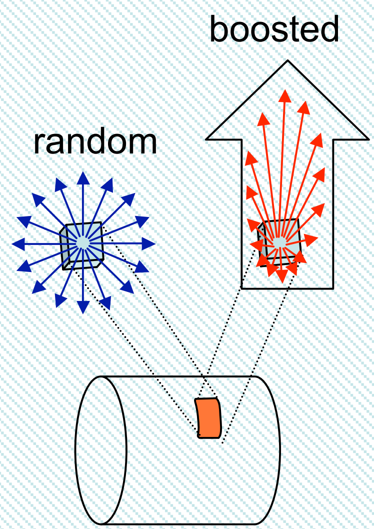
- Local thermal equilibrated
- Boosted radially

E.Schnedermann, J.Sollfrank, and U.Heinz, Phys. Rev. ***C48****, 2462(1993)*

$$E\frac{d^3N}{dp^3} \propto \int_{\sigma} e^{-(u^{\nu} p_{\nu})/T_{fo}} \, p d\sigma_{\mu}$$

$$\frac{dN}{m_T dm_T} \propto \int_0^R r dr\, m_T K_1\left(\frac{m_T \cosh\rho}{T_{fo}}\right) I_0\left(\frac{p_T \sinh\rho}{T_{fo}}\right)$$

$$\rho = \tanh^{-1}\beta_r \qquad \beta_r = \beta_S\left(\frac{r}{R}\right)^{\alpha} \qquad \alpha = 0.5, 1, 2$$



Thermal fits: T_{fo} vs. $< \beta_T >$

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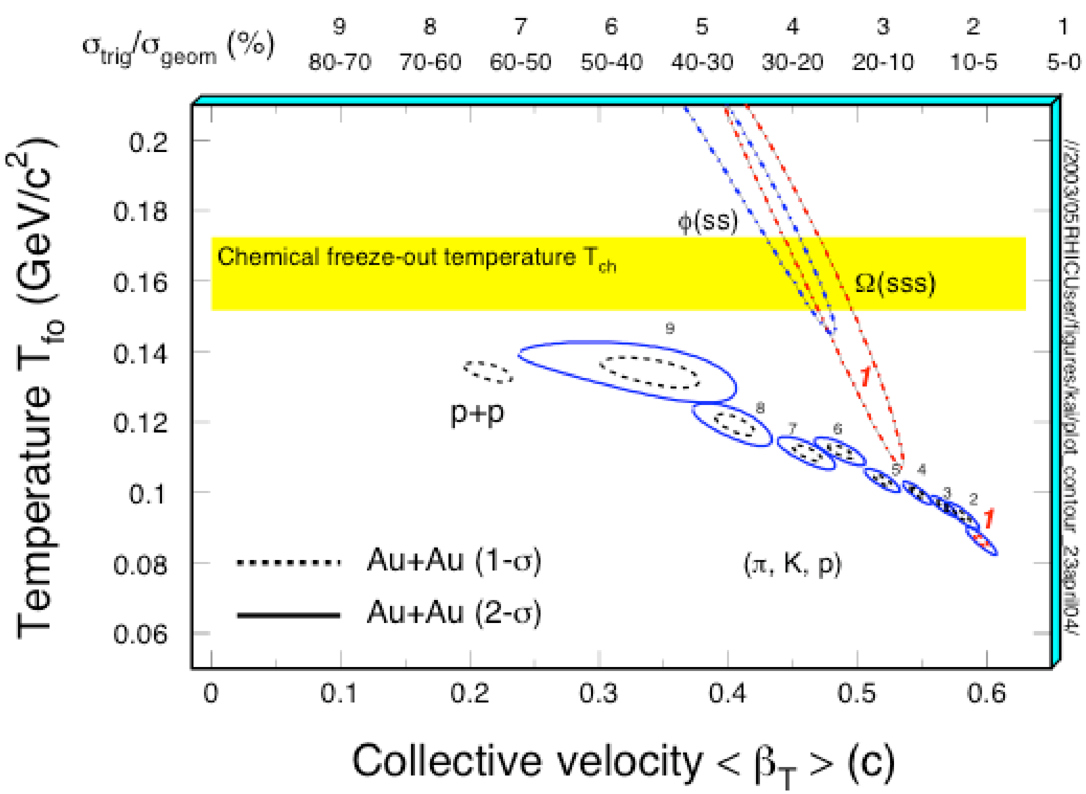
200GeV Au + Au collisions



Chemical Freeze-out: inelastic interactions stop
Kinetic Freeze-out: elastic interactions stop

1) π, *K*, and *p* change smoothly from peripheral to central collisions.
2) At the most central collisions, $<\beta_T>$ reaches 0.6c.
3) Multi-strange particles ϕ, Ω are found at higher T_{fo} ($T \sim T_{ch}$) and lower $<\beta_T>$

➪ **Sensitive to early partonic stage!**
➪ **How about v_2?**

Data: STAR: NP**A715**, 458c(03); *PRL* ***92**, 112301(04); **92**, 182301(04).*
NA49: *nucl-ex/0409004*

Chemical fits: Braun-Munzinger, Redlich, Stachel, *nucl-th/0304013*

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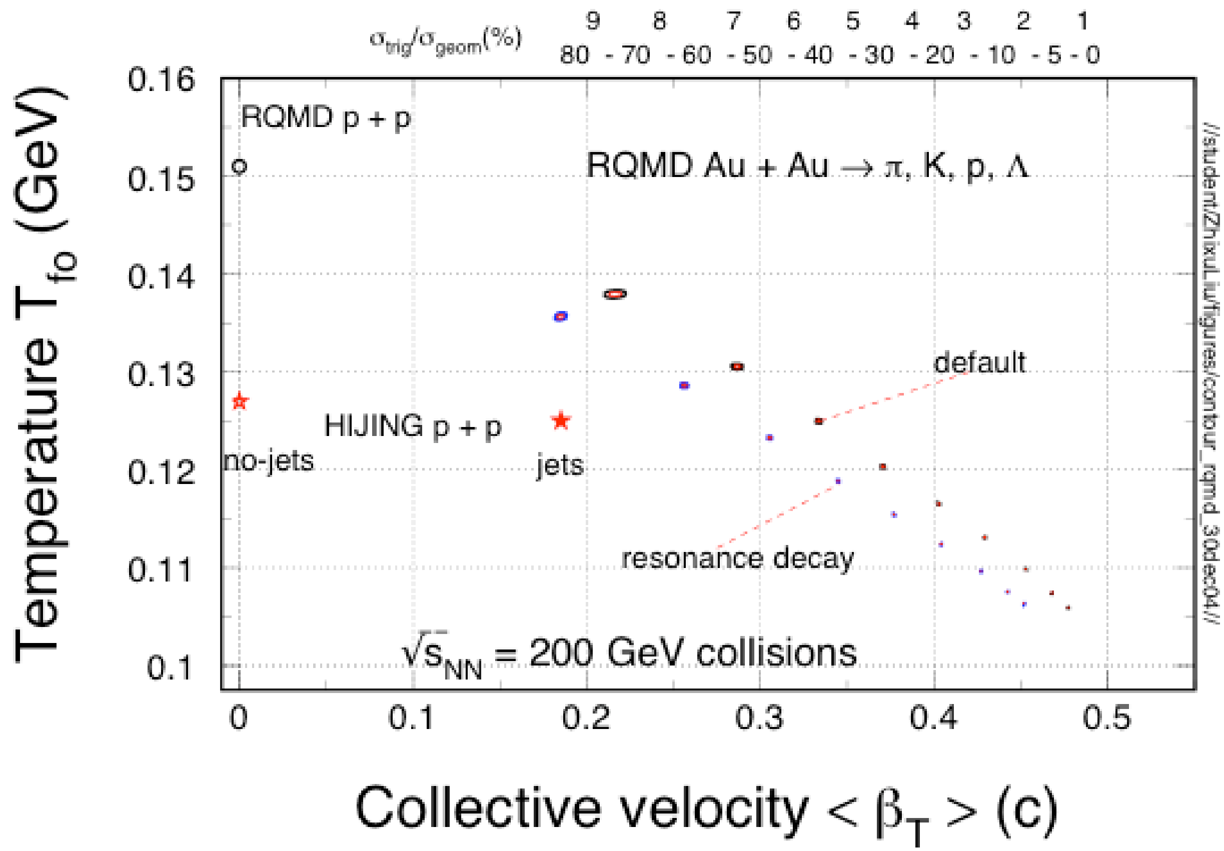
Resonance decay tests

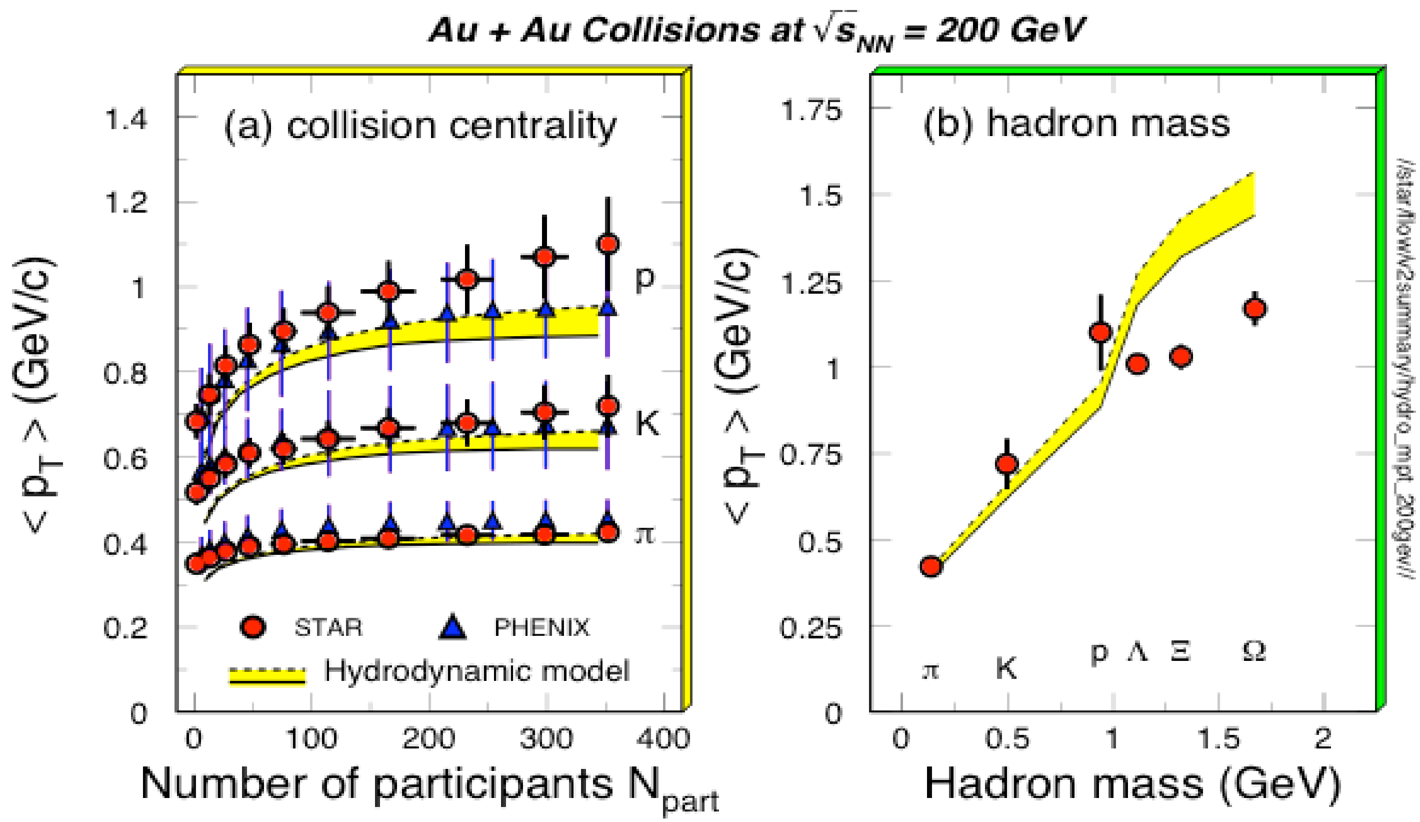


(1) Resonance decay of ▯, ▯, ▯, ▯ do not affect the freeze-out properties - there are life after the chemical freeze-out!

(2) ‘Jets’ lead to finite in p+p collisions

Zhixu Liu et al., December 2004.

Compare with Model Results

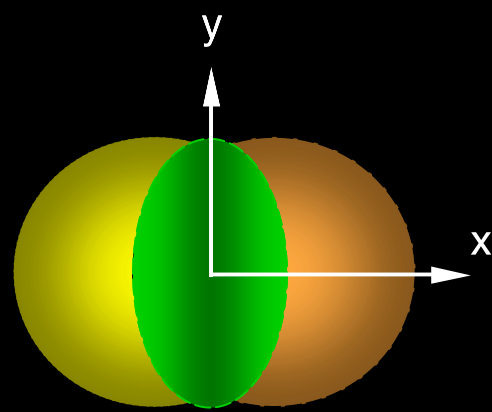


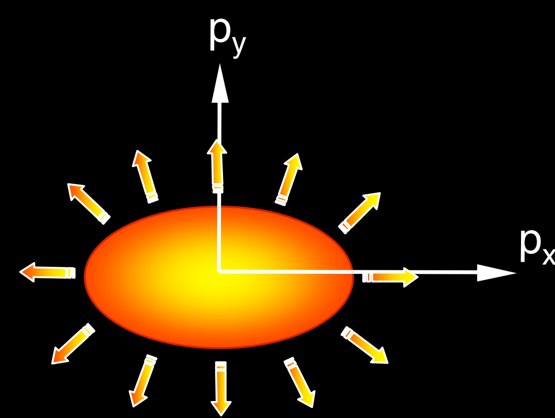
Model results fit to π, *K*, *p* spectra well, but over predicted <p_T> for multi-strange hadrons - **Do they freeze-out earlier?**

Phys. Rev. ***C69*** *034909 (04); Phys. Rev. Lett.* ***92****, 112301(04);* ***92****, 182301(04); P. Kolb et al., Phys. Rev.* ***C67*** *044903(03)*

Anisotropy Parameter v_2

coordinate-space-anisotropy ⇒ momentum-space-anisotropy





$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle} \qquad v_2 = \langle \cos 2\varphi \rangle, \quad \varphi = \tan^{-1}\left(\frac{p_y}{p_x}\right)$$

Initial/final conditions, EoS, degrees of freedom

v_2 at low p_T region

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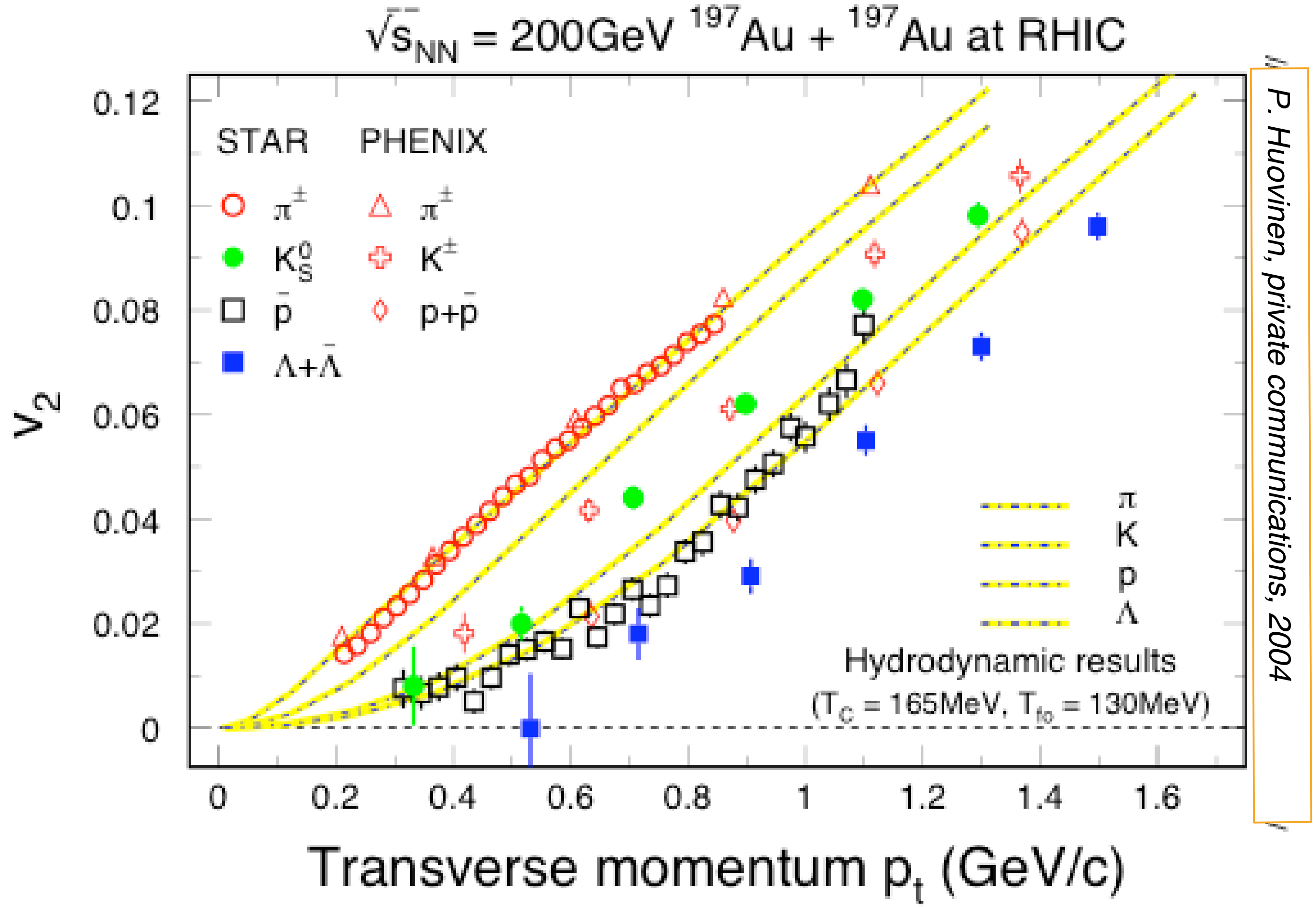
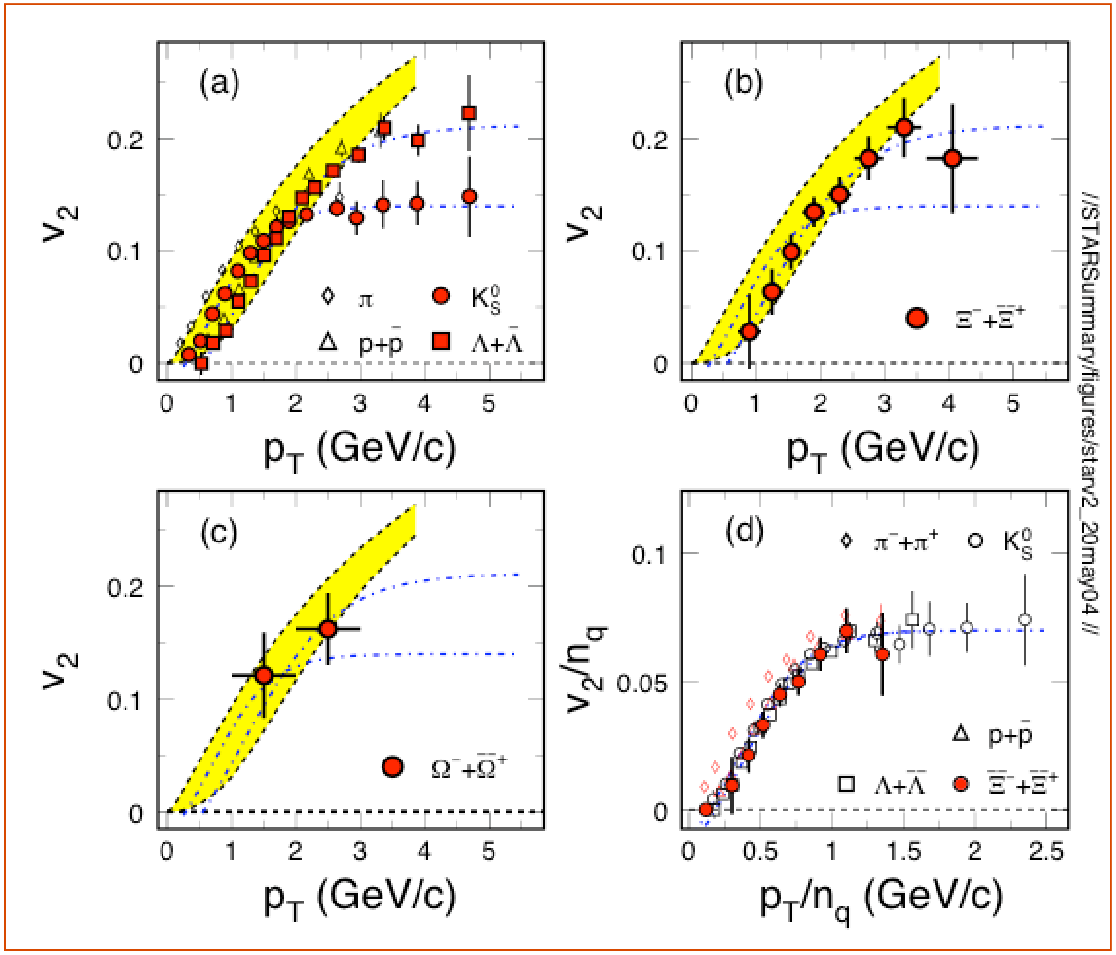


- Minimum bias data! At low p_T, model result fits mass hierarchy well!
- Details does not work, need more flow in the model!

v_2 at all p_T



- v_2, spectra of light hadrons and multi-strange hadrons
- scaling of the number of constituent quarks

At RHIC:

⇨ **Partonic collectivity has been attained**

⇨ **Deconfinement has has been attained**

*PHENIX: PRL**91**, 182301(03)*
*STAR: PRL**92**, 052302(04)*

S. Voloshin, NPA715, 379(03)
*Models: Greco et al, PR**C68**, 034904(03)*
*X. Dong, et al., Phys. Lett. **B597**, 328(04).*
….

Partonic Collectivity at RHIC

1) Copiously produced hadrons freeze-out:

T_{fo} = 100 MeV, □$_T$ = 0.6 (c) > □$_T$(SPS)

2)* Multi-strange hadrons freeze-out:

T_{fo} = 160-170 MeV (~ T_{ch}), □$_T$ = 0.4 (c)

3)** Multi-strange v_2:

Multi-strange hadrons □ and □ flow!

4)*** Constituent Quark scaling:

Seems to work for v_2 and R_{AA} (R_{CP})

Deconfinement

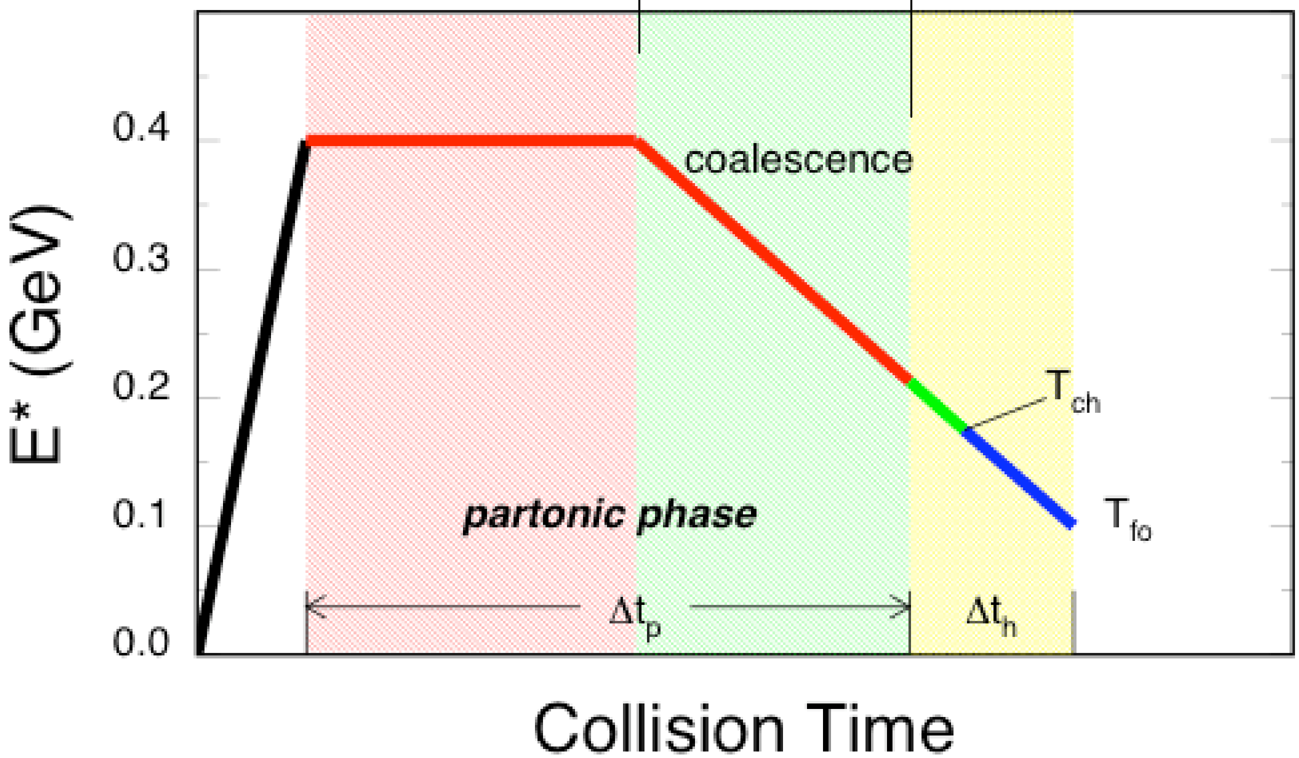
Partonic (*u,d,s*) Collectivity

Time Scale

deconfinement

Phase and Chiral transitions

u-, d-quarks and 'bound-states' gain mass



1) *Coalescence processes occur during phase transition and hadronization;*
2) *The u-,d-quarks and 'bound-states' gain mass accompanied by expansion;*
3) *Early thermalization with partons and its duration need to be checked.*

Open charm production at RHIC

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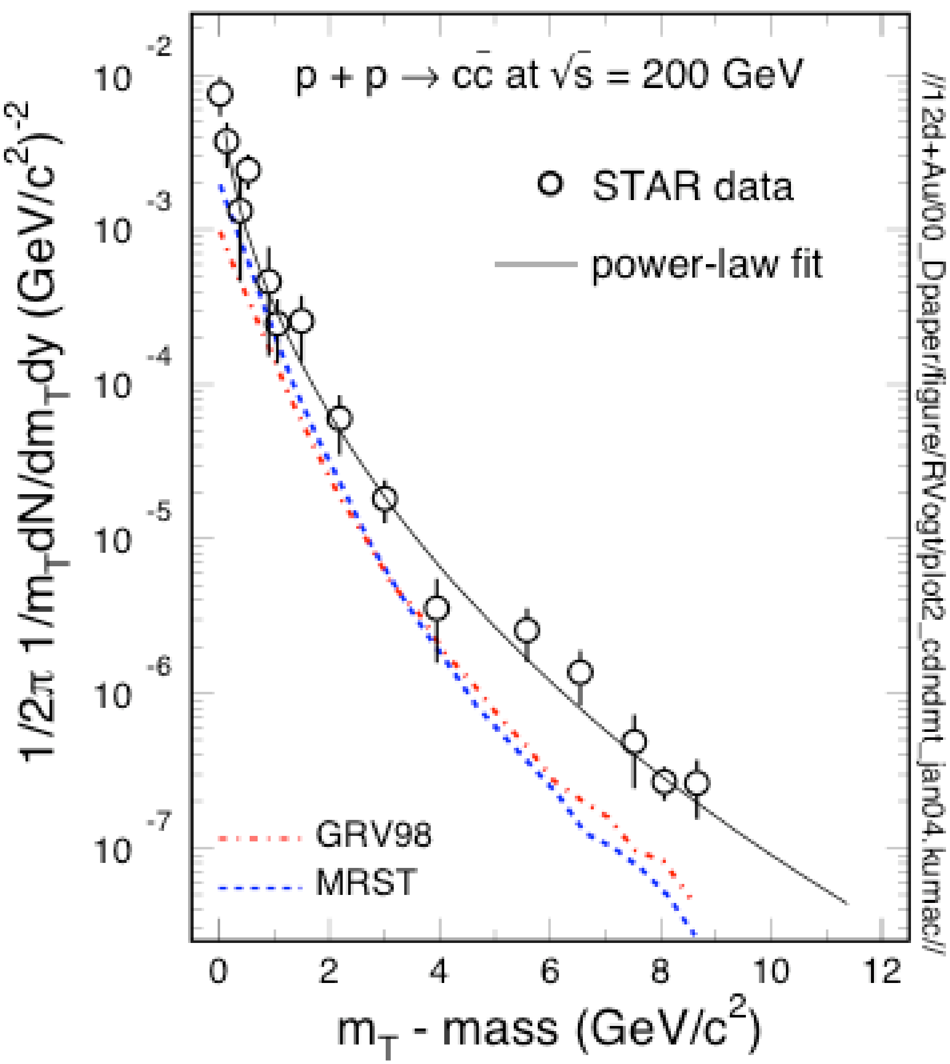

- First reconstructed open charm spectrum at RHIC

Model:

a) pQCD distributions are steeper

b) Fragmentation with delta function has harder spectrum

c) Total cross sections are lower, a factor of 3-5

- STAR data: *A. Tai et al., J. Phys* ***G30****: S809(2004);* nucl-ex/0404029

- model results: *R. Vogt, 2004*

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Charm production

1) STAR and PHENIX results are different:

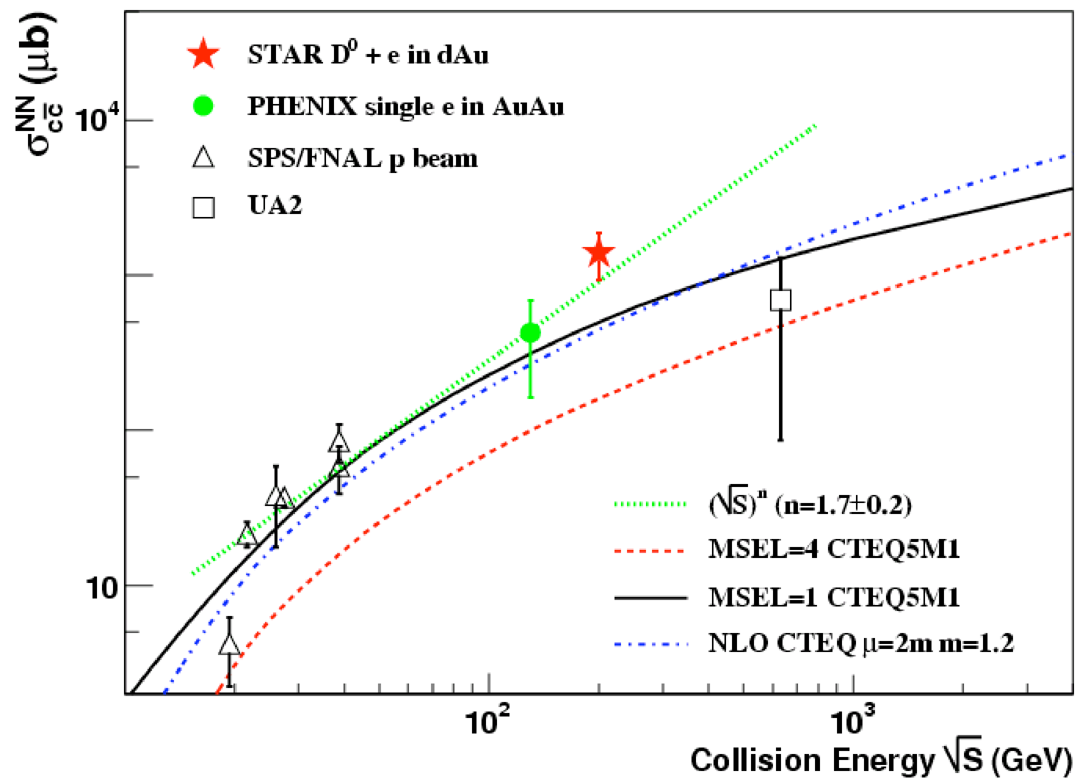
$$\sigma_{c\bar{c}}^{total} = 700 - 1200 (\mu b)$$

2) NLO pQCD calculations under-predict the ccbar production cross section at RHIC

3) Power law for ccbar cross section from SPS to RHIC: **n ~ 2** (n~0.5 for charged hadrons)

4) Large uncertainties in total cross section due to rapidity width, model dependent(?).

STAR data: PRL accepted, nucl-ex/0407006



Non-photonic electron v_2

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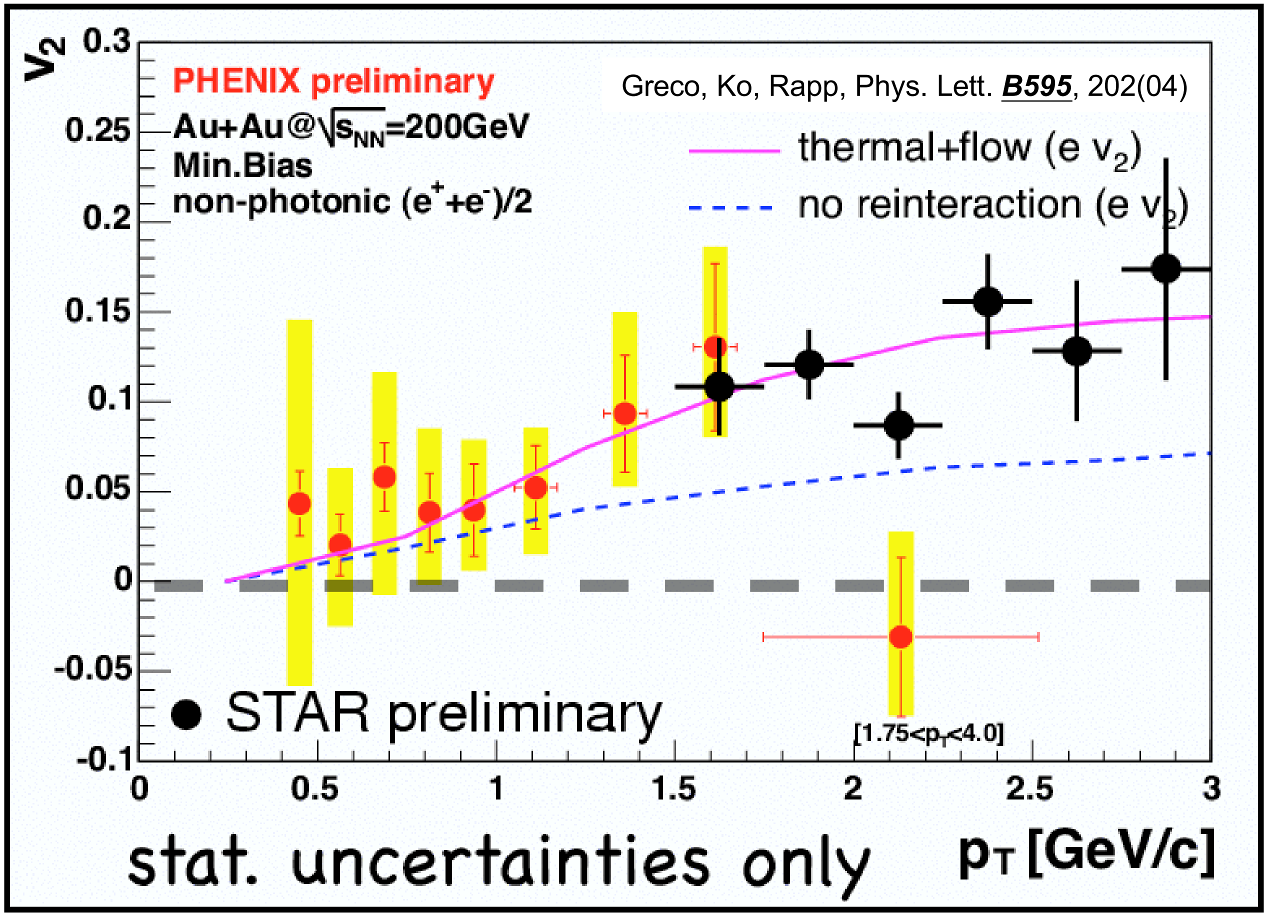

STAR: 0-80% (F.Laue SQM04)
statistical error only
corrected for $e^{\pm}$ from decay

PHENIX: Minimum bias

M. Kaneta *et al*, J.Phys. **G30**, S1217(04)

Open charm v_2 - a comparison

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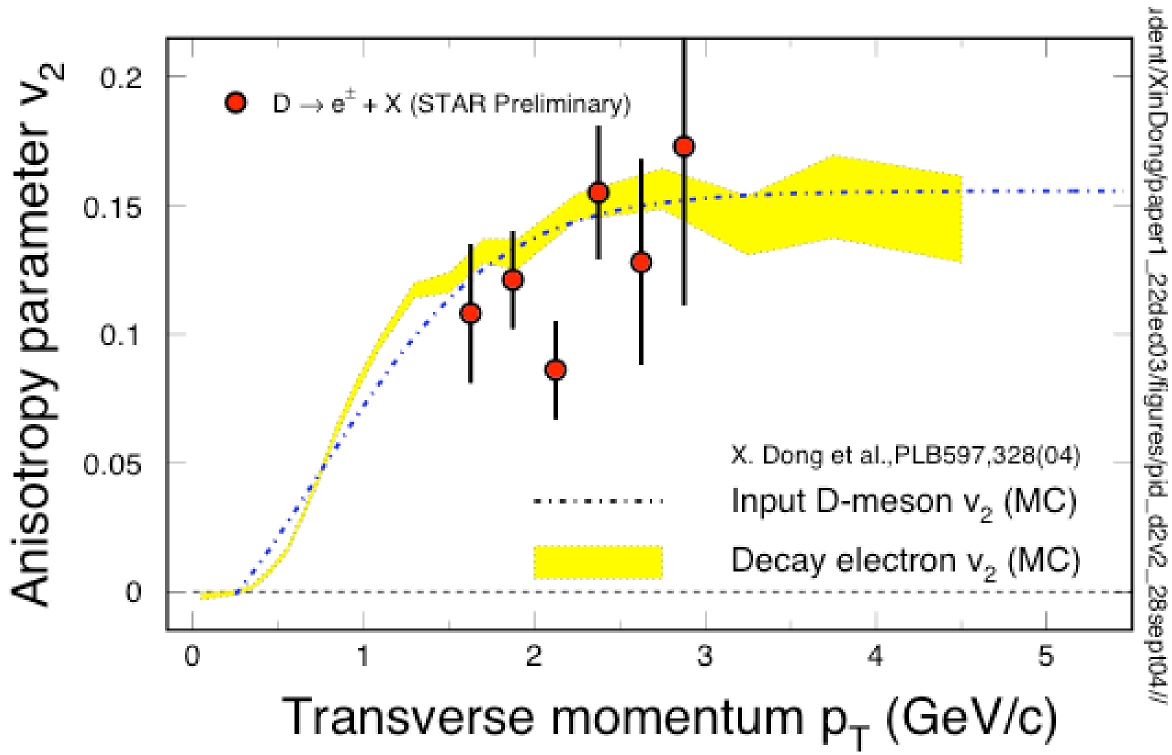

1) *Constituent Quark Scaling for open charm hadron production?*
2) *Flow of charm-quark and the thermalization among light flavors?*
3) *…????*

HSD: E. Bratkovskaya et al., hep-ph/0409071
X. Dong, S. Esumi, et al., Phys. Lett. ***B597****, 328(2004).*

Summary & Outlook

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(1) Collectivity - pressure gradient ∂P_{QCD}

➪ **Deconfinement and partonic collectivity at RHIC**

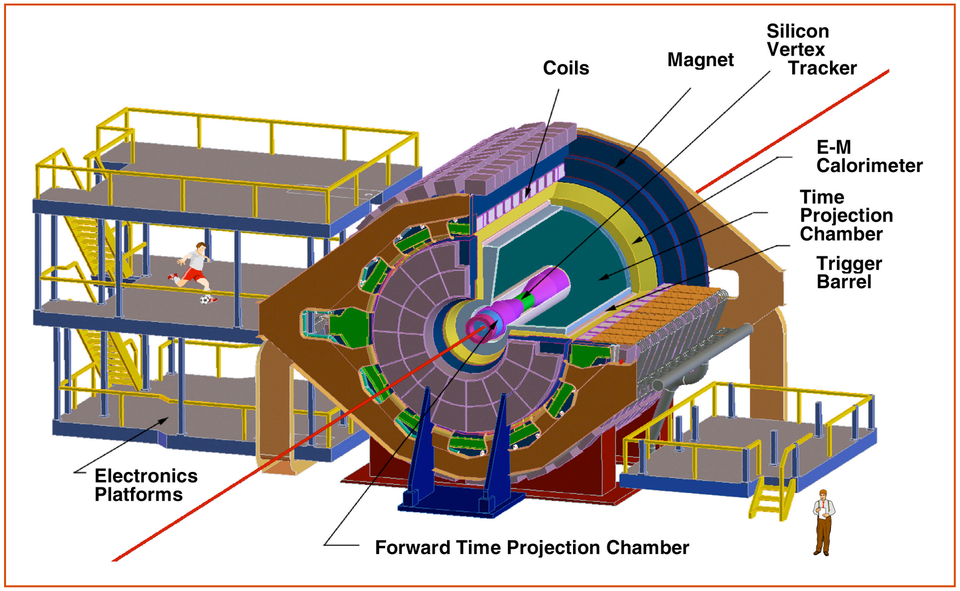
(2) Partonic (*u,d,s*) thermalization

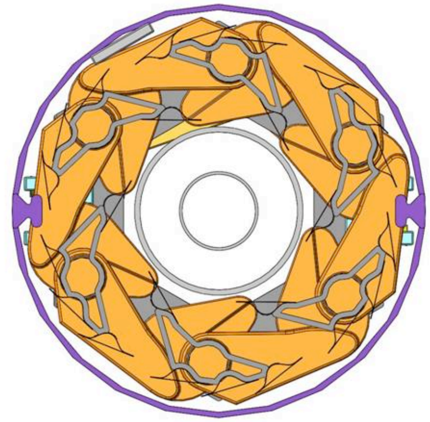
- heavy flavor v_2 and spectra
- di-lepton and thermal photon spectra
- J/ production

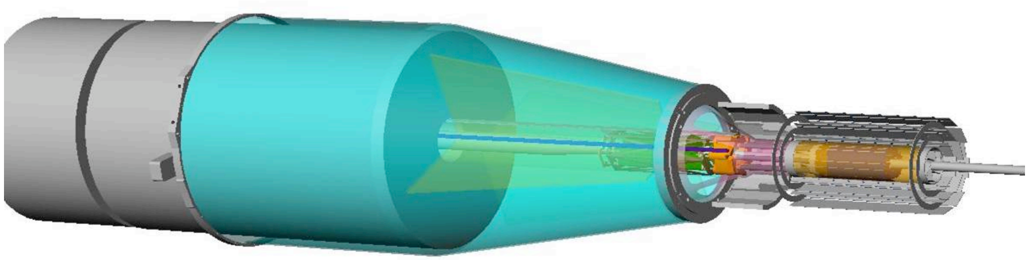
(3) -vertex upgrades Phenix and STAR

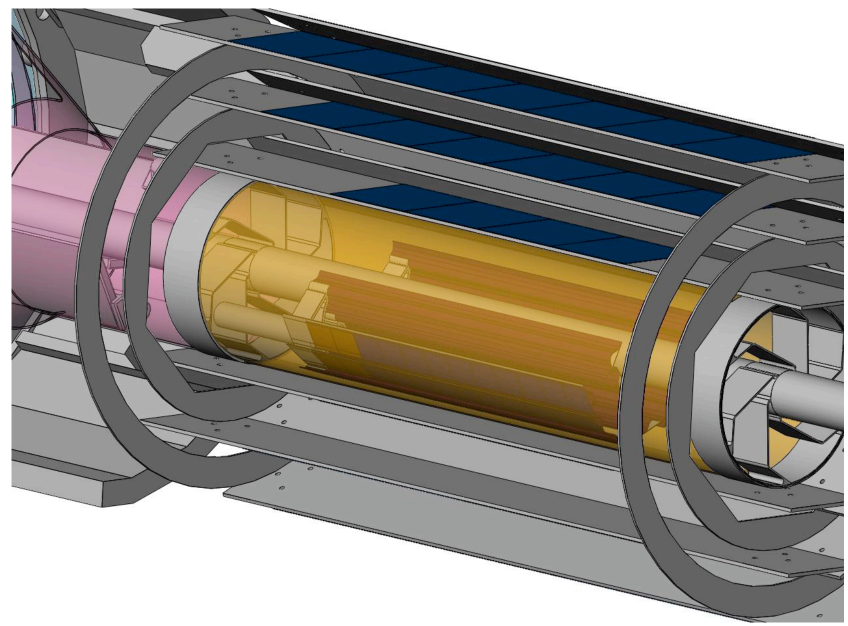
- open charm
- resonances with both hadronic & leptonic decays

STAR μ-vertex detector









H. Wieman et al., STAR Collaboration

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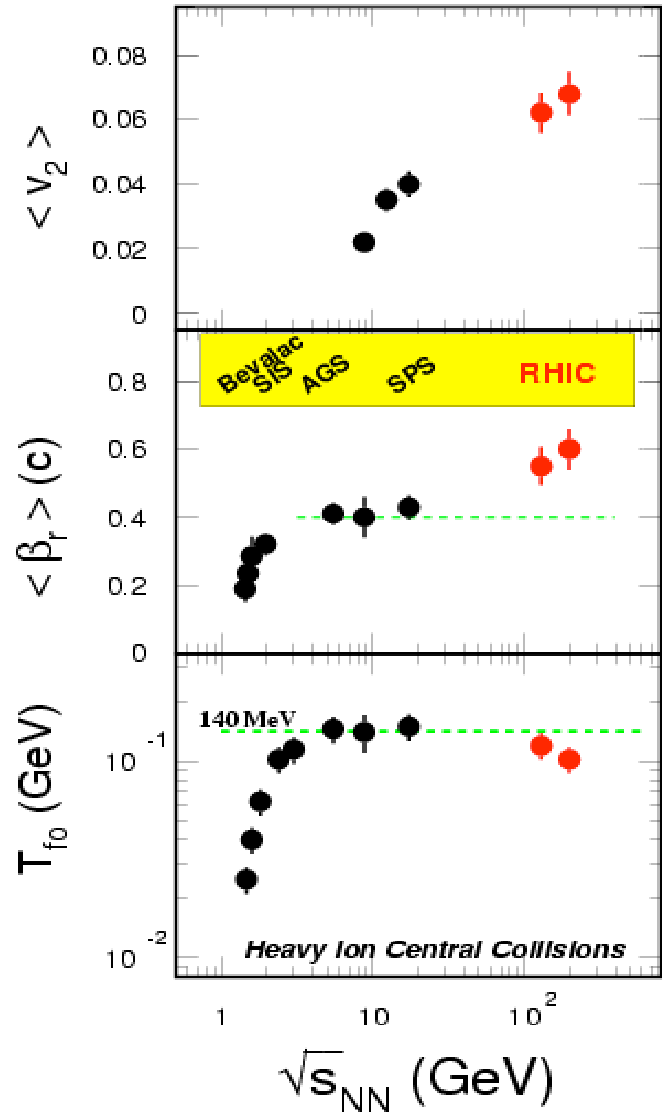
Bulk Freeze-out Systematics



The additional increase in β_T is likely due to partonic pressure at RHIC.

1) v_2 self-quenching, hydrodynamic model seem to work at low p_T
2) Multi-strange hadron freeze-out earlier, $T_{fo} \sim T_{ch}$
3) Multi-strang hadron show strong v_2

Nuclear Modification Factor

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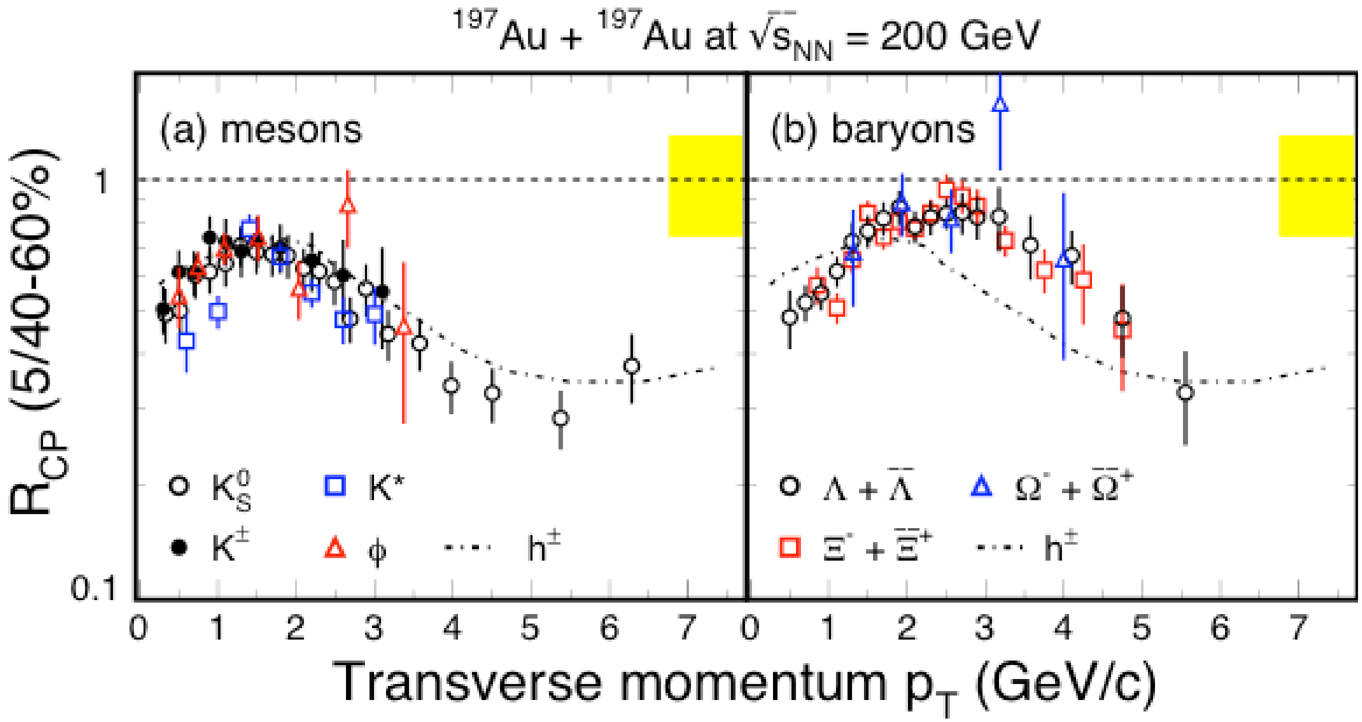

$$R_{CP}(p_T) = \frac{d^2N^{central} / (N^{central}_{binary}\, dp_T dy)}{d^2N^{peripheral} / (N^{peripheral}_{binary}\, dp_T dy)}$$

1) Baryon vs. meson effect!

2) Hadronization via coalescence

3) Parton thermalization (model)

- (K^0, □): *PRL**92**, 052303(04); NP**A715**, 466c(03);*
- *Greco et al, PR**C68**,034904(03);PRL**90**, 202102(03)*
- *R. Fries et al, PR**C68**, 044902(03);), Hwa, nucl-th/0406072*